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Performances and emissions of a petroleum coke oil slurry engine

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Abstract: In order to solve the failure of fuel system when using petroleum coke oil slurry (PCOS) in a R180 diesel engine directly, a petroleum coke oil slurry fuel system (PCOSFS) was developed and installed in R180 engine, which was called PCOS engine. In order to analyze performances and emissions of the PCOS engine, a comparative experiment between PCOS engine fueled with PCOS and R180 engine fueled with diesel oil was carried out. The results show that the PCOS engine can run smoothly, the maximum output power decreases by about 6.2% and 19.0% and the maximum brake thermal efficiency reduces by around 5.85% and 4.13% as compared to R180 engine under the conditions of 1 200 and 1 600 r/min. The HC emissions of PCOS engine are lower than those of R180 engine at 1 200 r/min, and are close to those of R180 engine at 1 600 r/min. The CO emissions are similar to R180 engine at 1 200 and 1 600 r/min. The smoke intensity is close to R180 engine at 1 200 r/min, and is higher than R180 engine at 1 600 r/min. The particles emitted from PCOS engine array sparsely, but particles emitted from R180 engine array closely, cohering together.

Key words: diesel oil; petroleum coke oil slurry; compression ignition engine; emissions

1 Introduction

Our society is widely dependent on petroleum. About 90% of the petroleum consumed annually is used as an energy source for transportation and for the generation of heat and electricity. The remaining 10% is used by the petrochemical and chemical industry as raw material. Since petroleum is a finite resource, its price will inevitably rise when it becomes limited. Hence, petroleum needs to be replaced by alternative and sustainable sources of energy in the near future [1]. There are many research reports about biodiesel [2−3], natural gas [4], ethanol [5], dimethyl ether [6], hydrogen [7], etc, which are recognized as alternatives to fossil fuels. A substitute fuel for diesel engines is produced from inedible animal tallow and its usability is investigated as pure biodiesel and its blends with petroleum diesel fuel in a diesel engine. Tallow methyl ester as biodiesel fuel is prepared by base-catalyzed transesterification of the fat with methanol in the presence of NaOH as catalyst [8]. Melon seeds containing ~30% oil are wasted after the fruit is consumed. The chemical and physical properties of melon seed oil are very similar to those of vegetable oils used as biodiesel fuel. Oil was extracted from waste melon seeds and transformed to melon seed oil methyl ester by transesterification process. This fuel was used in a four-stroke single-cylinder direct injection diesel engine, and its effects on performance and emissions were investigated for various engine speeds at full load [9]. The use of inedible vegetable oils as an alternative fuel for diesel engine is accelerated by the energy crisis due to depletion of resources and increased environmental problems including the great need for edible oil as food and the reduction of biodiesel production cost, etc. A lot of inedible vegetable oils which can be exploited for substitute fuel as diesel fuel, include jatropha, karanja, mahua, linseed, rubber seed, cottonseed, neem oils, etc [10].

There are also many researches about the application of the internal combustion engine for coal, coal-bed gas, charcoal, etc. An analytical model of a two-stroke cycle, reciprocating, compression ignition engine was used to investigate the ignition and combustion characteristics of coal water slurry fuels. A testing of coal water slurry in a single-cylinder, slow speed engine was conducted. The combustion of coal slurry, using water, diesel fuel, and methanol as carrier liquids, was investigated in a single-cylinder research engine [11−13]. A kind of low-viscosity light oil-coal-water fuel has been developed which has

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advantages of coal oil slurry and coal water slurry, and can be used as a replacement for oil burning in blast furnaces and boilers and has the potential to be used as an alternative for diesel oil in internal combustion engine [14]. An ultra-clean superfine coal oil slurry has been developed on the basis of the high-pressure jet comminution technique, which can be used as fuel in a high-speed diesel engine [15]. Coal-bed gas has been considered as an attractive alternative fuel for internal combustion engines due to its abundant source and low emissions. A combustion system with a swirl chamber has been developed for a spark-ignition engine using coal-bed gas [16]. Charcoal-based water slurries are shown to result in dramatically reduced engine abrasion problems compared to coal [17]. The renewable biomass charcoal-diesel slurries are used as alternative fuels for combustion in diesel generating plants. The utilization of charcoal slurry fuel aims to reduce diesel oil consumption and would decrease fossil green house emissions into the atmosphere [18].

Petroleum coke is a byproduct of the oil refining industry. It has high heating value and low price. Owing to the increasing demand for petroleum processing, the production of petroleum coke increases [19]. At present, the petroleum coke has mostly been burned in the boiler as fuel [20]. The petroleum coke has also been used to prepare syngas ($CO+H_2$) as the feedstock [21]. By using potassium carbonate as the catalyst for the steam gasification, petroleum coke could be feasibly used as raw material for the catalytic steam gasification at relatively low temperatures to produce gases with high H_2 and no virtual CH_4 [22]. High-sulfur petroleum coke is used as precursor in the preparation of natural gas adsorbents with chemical activation [23]. In order to enlarge the species of alternative fuels and effectively enhance the application value of the petroleum coke, the application of the petroleum coke in the engine as alternative fuels has been explored [24−25]. The experimental investigation of petroleum coke oil slurry (PCOS) engine was performed in this work.

2 Experiment

The experimental setup consists of a dynamometer, a compression ignition engine, a petroleum coke oil slurry fuel system (PCOSFS), an electronic balance, thermocouples with temperature indicator, an exhaust gas analyzer and a smokemeter. The schematic diagram of the experimental setup is shown in Fig. 1. The dynamometer is CW50 type eddy current dynamometer. The engine is R180 type, single cylinder, horizontal type, cooled by evaporation, four-stroke, swirl combustion chamber and compression ignition engine. The engine specifications are given in Table 1.

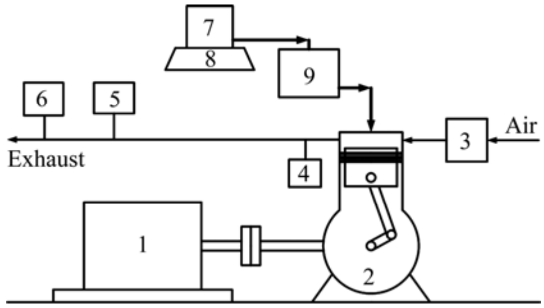

Fig. 1 Schematic diagram of experimental setup: 1—Dynamometer; 2—Engine; 3—Air filter; 4—Thermocouple with temperature indicator; 5—Smokemeter; 6—Exhaust gas analyzer; 7—Fuel tank; 8—Electronic balance; 9—PCOSFS

Table 1 Engine main specifications

Parameter	Value
Rated power/kW	5. 67
Rated speed/($r \cdot min^{-1}$)	2 600
Number of cylinders	1
Bore/mm×Stroke/mm	80×80
Displacement volume/cm^3	402.12
Compression ratio	21:1
Injection pressure/MPa	13. 72±0.5

PCOSFS includes a PCOS pump, a PCOS injector and a cleaning and lubricating system. Owning to particles of PCOS easily causing the original engine (R180 type engine) fuel system to clog, the PCOSFS was developed. The schematic diagram of PCOS injector is shown in Fig. 2. Figure 2(a) shows the sectional view of the PCOS injector dissected along the high-pressure PCOS fuel inlet connection. The high-pressure PCOS flowed into the groove of the injector, and PCOS was sprayed into the combustion chamber by lifting the needle valve when the pressure of PCOS exceeded the pre-tightening force of the needle valve spring. A fraction of the PCOS penetrated simultaneously into the lubricating oil chamber through the fit clearance between the needle valve and the needle body. Figure 2(b) shows the sectional view of the PCOS injector dissected along the lubricating oil connector. The lubricating oil circulated constantly and took PCOS away from the lubricating oil chamber, preventing the particles of PCOS from accumulating in the lubricating oil chamber and seizing the needle valve. Besides, columniform pintle of needle valve was converted into cone. After the cone was inserted in the orifice, the space between the cone and the orifice increased compared with the pintle, and the accumulation of PCOS particles in the orifice was mitigated. When passing through the orifice, the high pressure PCOS was in collision with the surface of the cone and then atomized, so there was no coking in the

nozzle. The pressure surface of the needle valve was modified from original conical surface to torus, thus the space of the PCOS groove was enlarged, and the particles that deposited on the bottom of the groove failed to stick to the pressure surface, preventing the action of the needle valve from being stopped due to the pressure surface of the needle valve being squeezed by the particles.

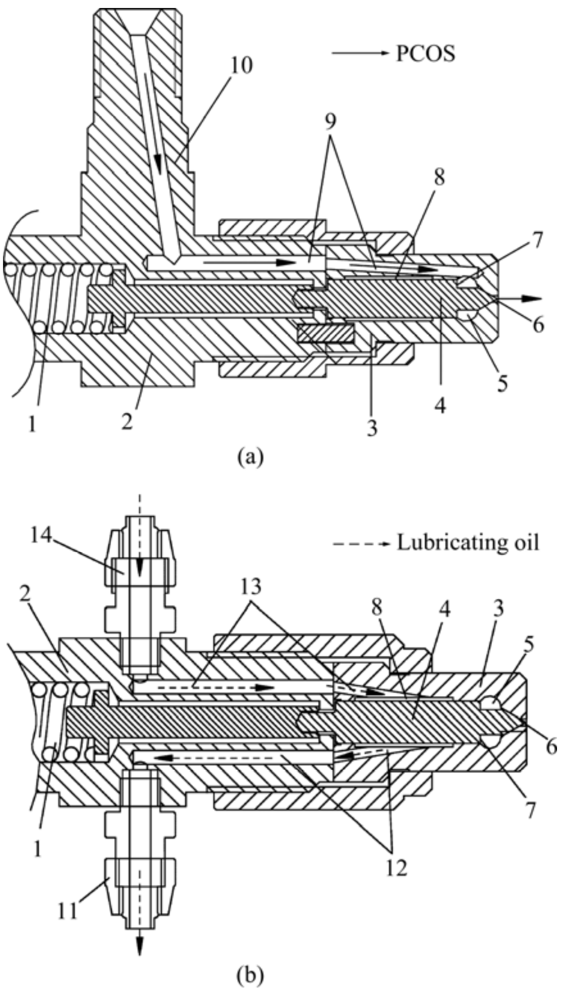

Fig. 2 Schematic diagrams of PCOS injector: (a) Sectional view of PCOS injector dissected along high-pressure PCOS fuel inlet connection; (b) Sectional view of PCOS injector dissected along lubricating oil connector (1—Needle valve spring; 2—PCOS injector holder; 3—Nozzle body; 4—Needle valve; 5—PCOS groove; 6—Orifice; 7—Pressure surface of needle valve; 8—Lubricating oil chamber of nozzle body; 9—High pressure PCOS gallery; 10—High pressure PCOS fuel inlet connection; 11—Lubricating oil outlet connector; 12—Lubricating oil outlet gallery; 13—Lubricating oil inlet gallery; 14—Lubricating oil inlet connector)

The schematic diagram of PCOS pump is shown in Fig. 3. Owing to being pushed by the plunger, the low pressure PCOS in the plunger compartment was converted into high pressure PCOS, which flowed into the PCOS injector through the delivery valve. At the same time, a fraction of PCOS penetrated into the lubricating oil chamber through the fit clearance between the plunger and the plunger sleeve, and the PCOS was taken out of the chamber by lubricating oil, which prohibited particles of PCOS from seizing the plunger. The schematic diagram of the cleaning and lubricating system of the PCOS pump and injector is shown in Fig. 4. The driving gear was installed at the end of the camshaft and drove the lubricating oil pump. The circulation flow of the lubricant oil under the action of the lubricating oil pump took the particles of PCOS away from the lubricating oil chambers of the nozzle body and the plunger sleeve, and the particles reflowed into the lubricating oil vessel. Unless becoming dirty, the oil would not be replaced by the fresh oil. The cleaning and lubricating system could use the diesel oil as the lubricating oil, and the dirty diesel oil could be poured into the PCOS and be used as fuel.

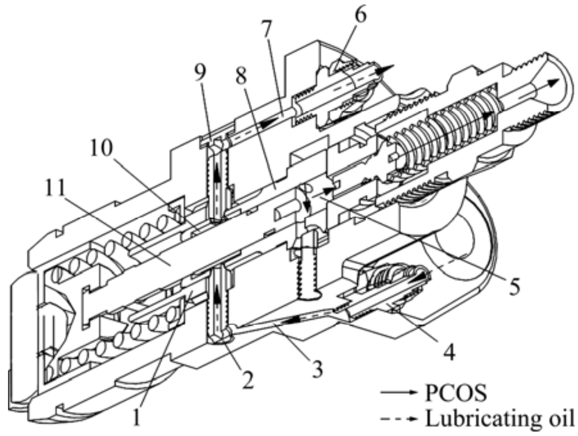

Fig. 3 Schematic diagram of PCOS pump: 1—Control pinion; 2—Lubricating oil inlet hollow bolt; 3—Lubricating oil inlet gallery; 4—Lubricating oil inlet connector; 5—Plunger compartment; 6—Lubricating oil outlet connector; 7—Lubricating oil outlet gallery; 8—Plunger sleeve; 9—Lubricating oil outlet hollow bolt; 10—Lubricating oil chamber of plunger sleeve; 11—Plunger

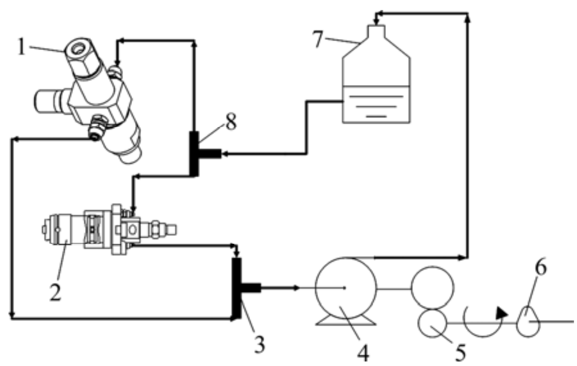

Fig. 4 Schematic diagram of cleaning and lubricating system of PCOS pump and injector: 1—PCOS injector; 2—PCOS pump; 3, 8—Tee joint; 4—Lubricating oil pump; 5—Driving gear; 6—Camshaft; 7—Lubricating oil vessel

The engine was connected with the dynamometer. The dynamometer was used to measure the engine speed and torque under different conditions. The installation positions of the PCOS pump and injector in the PCOS engine were the same to the original pump and injector in the R180 engine, the PCOS pump was driven by the camshaft, and the PCOS injector was mounted in the cylinder head. The injection pressure of the PCOS injector (about 14 MPa) was the same to the original injector. The FGA-4100 type exhaust gas analyzer was used to measure the volume fractions of HC, CO and NO_x emissions. The electronic digital indicator with K type thermocouple was used to measure the exhaust temperature. The 495/01 type opacity smokemeter was used to detect smoke intensity. A comparative experiment between PCOS engine fueled with PCOS and R180 engine fueled with diesel oil was carried out. The experiment began after the engine was warmed up fully. All data were measured under steady conditions.

The fuels used in the test were diesel oil and PCOS, and the fuel mass consumption was measured by a LT500B type electronic balance. The low heat value (LHV) of diesel oil (No. 0 diesel oil sold in Beijing city) is 42.5 MJ/kg, and its viscosity is about 3−8 mPa·s at room temperature. C and H contents are about 84.96% and 15.04%, respectively. PCOS was made up of petroleum coke powders and diesel oil, and the petroleum coke powders were prepared by ultrafine grinding to the petroleum coke using JFC-5 type jet mill. Figure 5 shows the scanning electron microscope photographs of the petroleum coke powders, and the average particle sizes of the powders are 9.6, 3.6 and 1.8 μm, respectively. The particle size of the petroleum coke powders is small and it is more difficult to clog the ducts and the clearances of the PCOSFS, which is favorable for atomization and combustion. Hence, the average size of 1.8 μm should be given prior consideration to prepare PCOS.

Table 2 gives the analysis results of petroleum coke. Petroleum coke oil slurries with different contents of petroleum coke powders were prepared by mixing petroleum coke powders of average size of 1.8 μm with diesel oil. A great deal of experiments show that the viscosity of PCOS increases with the increase of petroleum coke powders loading, and when the mass fraction of petroleum coke powders exceeds 30%, the viscosity of PCOS rises rapidly. High viscous PCOS goes against atomization and combustion, thus 30% PCOS was selected in this test. After adding additive NDZ-105, the viscosity of PCOS decreases to about 300 mPa·s at room temperature. The LHV of 30% PCOS is 40.3 MJ/kg approximately. Therefore, the viscosity of PCOS is higher and the LHV of PCOS is somewhat lower compared with the diesel oil, especially the PCOS includes some solid particles (petroleum coke powders). The traditional engine (R180 engine) cannot work when using the PCOS, but the PCOS engine can run steadily when using the PCOS. The PCOS may replace diesel oil in the PCOS engine.

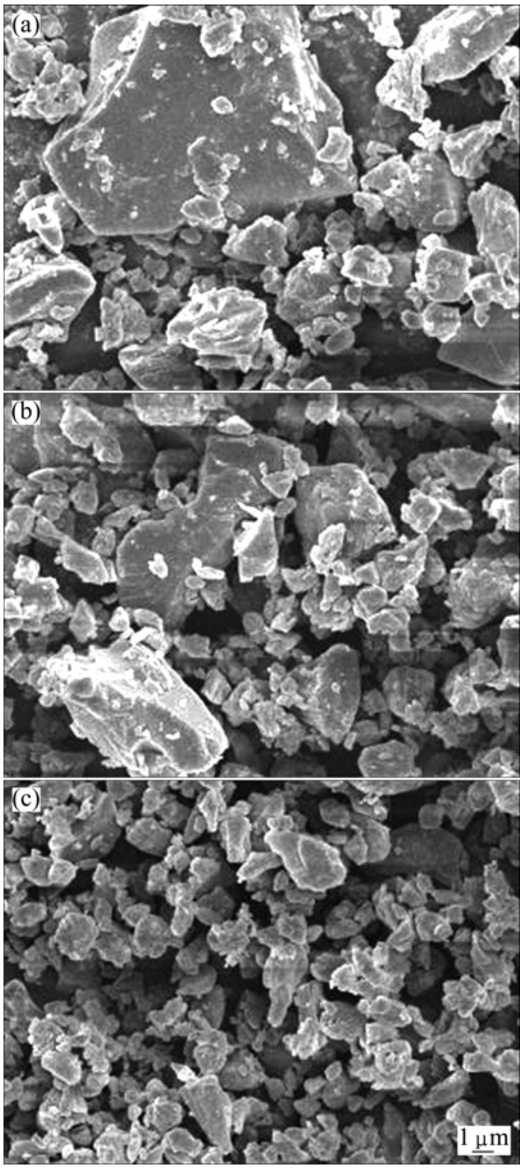

Fig. 5 Scanning electron microscope photographs of petroleum coke powders: (a) 9.6 μm; (b) 3.6 μm; (c) 1.8 μm

Table 2 Proximate analysis and ultimate analysis of petroleum coke

Sample	Proximate analysis				Ultimate analysis				LHV/
	w(Moisture)/%	w(Ash)/%	w(Volatile)/%	w(Fixed carbon)/%	w(N)/%	w(C)/%	w(S)/%	w(H)/%	$(MJ·kg^{-1})$
Petroleum coke	0.43	0.35	9.03	90.62	1.843	91.40	2.680	3.839	35.13

3 Results and discussion

The performances (including brake specific energy consumption (BSEC), brake thermal efficiency and exhaust gas temperature) and emissions (including gaseous emissions and particulate emissions) of engines fueled with diesel oil and PCOS were investigated experimentally. The test of the original R180 type engine fueled with diesel oil was performed, and the test of the PCOS engine fueled with PCOS was also carried out. All the tests with different fuels were conducted at engine speeds of 1 200 and 1 600 r/min and at different engine loads. Before each test was finished, the PCOSFS was flushed by using diesel oil, avoiding the particles of PCOS to accumulate and deposit in the pipe and gallery of PCOSFS.

3.1 Brake specific energy consumption

Figure 6 shows the variation of BSEC for diesel oil and PCOS. At a constant speed, the fuel quantity of the engine increases gradually till the output power of the engine is the maximum at this speed. Figure 6 indicates that the BSEC is higher for PCOS compared to diesel oil at the same speed. Though the LHV of PCOS is lower than diesel oil, BSEC is higher for PCOS compared to diesel oil at the same speed; in other words, PCOS increases BSEC. As the engine speed increases, the maximum output power of the PCOS engine fueled with PCOS declines by about 6.2% and 19.0%, respectively, compared with R180 engine fueled with diesel oil. This is due to the low LHV and poor combustion performance of PCOS. The ignition delay and combustion duration of the particles in PCOS are longer than those of diesel oil. Therefore, some particles of late ignition are not able to combust completely and finally emit with the exhaust gas. As the engine speed increases, the quantity of petroleum coke particles emitted from the combustion chamber increases, and the difference of the maximum output power is enlarged between burning diesel oil and PCOS.

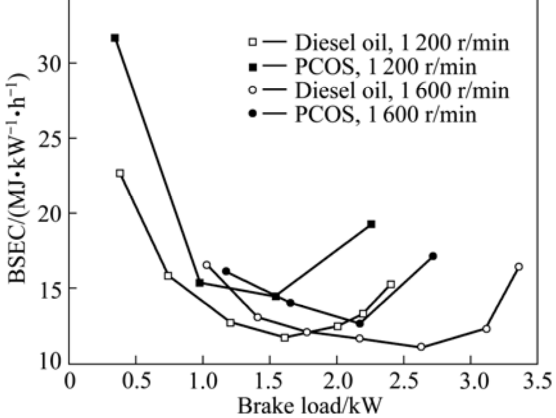

Fig. 6 Comparison of BSEC for diesel oil and PCOS

3.2 Brake thermal efficiency

Figure 7 shows the variation of brake thermal efficiency as a function of brake load for diesel oil and PCOS. At the speed of 1 200 and 1 600 r/min, the brake thermal efficiency of PCOS engine fueled with PCOS is lower than that of R180 engine fueled with diesel oil, and the maximum brake thermal efficiency is 24.95% and 28.45% for PCOS, as compared to 30.8% and 32.58% for diesel oil, and the maximum brake thermal efficiency for PCOS decreases by 5.85% and 4.13% compared to diesel oil. Because the viscosity of PCOS is higher than that of diesel oil and volatility of PCOS is lower than that of diesel oil at room temperature, atomization of PCOS is poor and combustion of PCOS is bad in the combustion chamber. Due to the longer ignition delay of PCOS than diesel oil, the petroleum coke particles of PCOS do not burn out completely, and some particles continue to burn in the exhaust pipe, and others are emitted into the atmosphere with the exhaust gas, resulting in higher heat loss and lower brake thermal efficiency for PCOS than diesel oil.

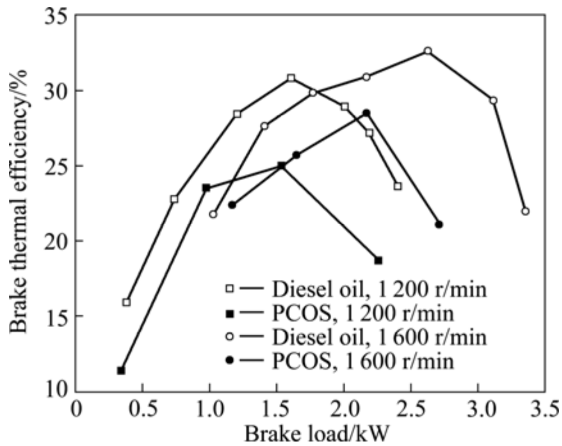

Fig. 7 Comparison of brake thermal efficiency for diesel oil and PCOS

3.3 Exhaust gas temperature

Figure 8 shows the variation of exhaust gas temperature for diesel oil and PCOS. Exhaust gas temperature is generally higher for PCOS than diesel at 1 200 and 1 600 r/min. Before the maximum output power point of the PCOS engine fueled with PCOS, the exhaust gas temperature for PCOS is 10−15 °C higher than that for diesel oil at 1 200 r/min, and it is very close to that for diesel oil at the maximum output power point at 1 200 r/min. As petroleum coke particles in PCOS do not burn out fully, they flow into the exhaust pipe and continue to burn and release heat, resulting in slightly higher exhaust gas temperature for PCOS compared to

diesel oil. The exhaust gas temperature for PCOS is 24−120 °C higher than that for diesel oil at 1 600 r/min, and the difference of exhaust gas temperature between PCOS and diesel oil at 1 600 r/min increases remarkably compared to the speed of 1 200 r/min. At high speed, shorter burning time of the PCOS engine fueled with PCOS results in more unburned petroleum coke particles, more heat released in the exhaust pipe and higher exhaust gas temperature for PCOS compared to diesel oil.

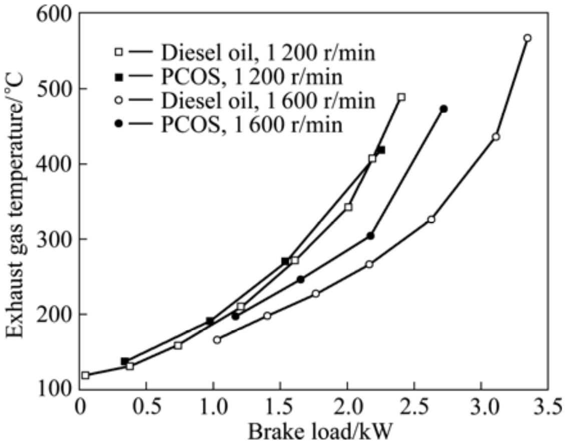

Fig. 8 Comparison of exhaust gas temperature for diesel oil and PCOS

3.4 Gaseous emissions

HC emissions of compression ignition engine mainly originate from incomplete combustion of fossil fuels such as diesel oil [26]. Figure 9 shows HC emissions for diesel oil and PCOS. It can be seen from these curves that HC emissions for diesel oil decrease with the increase of the engine speed. This is because of low swirl in the combustion chamber at low speed (1 200 r/min), and the mixture of the diesel oil and air in the combustion chamber is very inhomogeneous. With the increase of the speed, combustion condition is improved and the diesel oil in combustion chamber is burned better, so the HC emissions decrease.

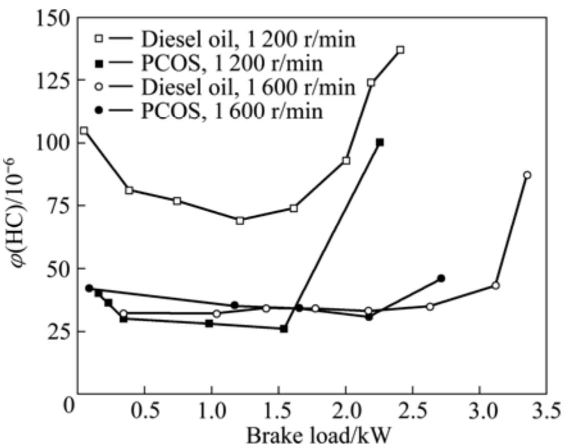

Fig. 9 Comparison of HC emissions for diesel oil and PCOS

Figure 9 also shows lower HC emissions for PCOS compared to diesel oil at 1 200 r/min. There are two main reasons for that. The first one is that less diesel fuel is injected into the engine cylinder when burning PCOS compared to burning diesel oil. The second one is that higher exhaust gas temperature for PCOS than diesel oil results in the intensification of oxidation of HC for PCOS. Figures 10 and 8 verify these two reasons. Before the maximum output power point for PCOS, the diesel fuel consumption for PCOS is lower than that for diesel oil at 1 200 r/min (Fig. 10), and the exhaust gas temperature for PCOS is higher than that for diesel oil at 1 200 r/min (Fig. 8). A combination of both reasons works, so the HC emissions for PCOS are significantly lower than those for diesel oil at 1 200 r/min. At 1 200 r/min, the diesel oil consumption of PCOS at the maximum output power point is very close to that of diesel oil under the same conditions (Fig. 10), so HC emissions are very close to each other too.

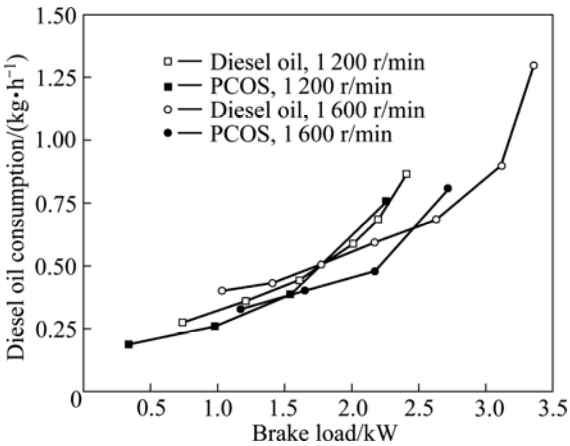

Fig. 10 Comparison of diesel oil consumption for diesel oil and PCOS

It can also be noticed from Fig. 9 that before the maximum output power point at 1 600 r/min, the HC emissions for PCOS are close to those for diesel oil, and at the maximum output power point, the HC emissions for PCOS are higher than those for diesel oil. Figure 10 represents that before the maximum output power point, the diesel oil consumption for PCOS is lower than that for diesel oil at 1 600 r/min. Due to the intensification of swirl in the cylinder and the well combustion of diesel oil, HC emissions are close at 1 600 r/min (Fig. 9). At the maximum output power point for PCOS and at 1 600 r/min, the diesel oil consumption for PCOS is higher than that for diesel oil under the same conditions (Fig. 10), so the HC emissions for PCOS increase compared to diesel oil (Fig. 9).

Figure 11 shows the variation of CO emissions for diesel oil and PCOS. Before the maximum output power point when burning PCOS, the CO emissions for PCOS are the same to those for diesel oil at 1 200 and 1 600

r/min. At the maximum output power point, the CO emissions for PCOS are higher than those for diesel oil under the same conditions. This is because there is ample oxygen available for the reaction before the maximum output power point when burning PCOS, CO has mostly been converted to CO_2 at last, and it is the same to diesel oil. Thereby, the CO emissions for diesel oil and PCOS are similar and the CO concentrations remain unchanged before the maximum output power point. At the maximum output power point for PCOS, the anoxic zones increase with the decrease of air-to-fuel ratio, and the CO emissions increase due to the incomplete combustion of CO. Moreover, the C/H mass ratio of PCOS is higher than that of diesel oil, so, at the maximum output power point, the CO emissions for PCOS are higher compared to diesel oil under the same conditions.

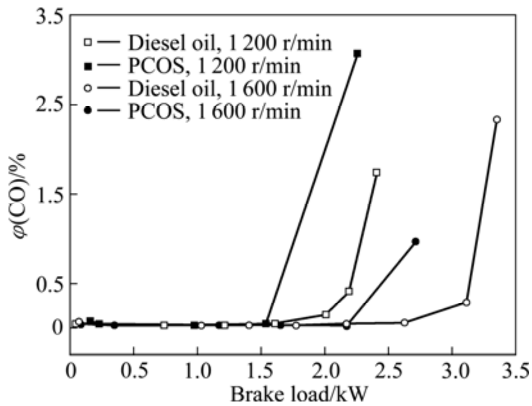

Fig. 11 Comparison of CO emissions for diesel oil and PCOS

Figure 12 shows the variation of NO_x emissions for diesel oil and PCOS. The NO_x emissions for PCOS are close to those for diesel oil at low engine loads. This is because of low combustion chamber temperature at low engine loads. With the increase of the engine loads, the NO_x emissions for PCOS are lower than those for diesel oil at 1 200 and 1 600 r/min. This is due to the difference of combustion characteristics between diesel oil and PCOS. The LHV of PCOS is lower than that of diesel oil. The ignition of diesel fuel in PCOS is prior to petroleum coke particles in PCOS. Owing to the longer ignition delay, the petroleum coke particles of incomplete combustion are emitted from the combustion chamber, and the combustion chamber temperature of PCOS engine is lower than that of R180 engine. When burning diesel oil in the R180 engine, the higher LHV and higher burning rate of diesel oil result in higher combustion chamber temperature and higher NO_x emissions compared to PCOS engine. It can also be noticed from Fig. 12 that NO_x emissions for diesel oil and PCOS appear to have a decline trend after an initial ascent. Owing to ample oxygen in the engine cylinder and low combustion chamber temperature, the NO_x emissions is low at low engine loads. With the increase of the engine loads and rise of combustion chamber temperature, the NO_x emissions for diesel oil and PCOS appear ascent trend. With further increase of the engine loads, there is relative short of oxygen in combustion chamber of engine, which leads to a bad combustion, so the NO_x emissions decrease [27].

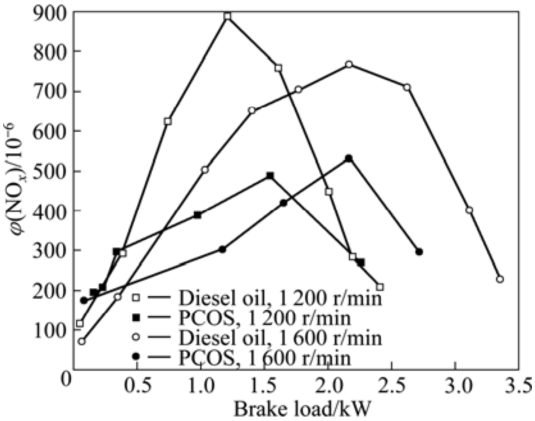

Fig. 12 Comparison of NO_x emissions for diesel oil and PCOS

3.5 Particulate emissions

In this work, the smoke intensity is indicated by extinction coefficient. Figure 13 shows the variation of extinction coefficient for diesel oil and PCOS. Before the maximum output power point for PCOS, the extinction coefficient of PCOS is close to that of diesel oil at 1 200 r/min. At the maximum output power point for PCOS, the extinction coefficient is lower compared to diesel oil at 1 200 r/min. This is because of relatively long time to stay in the combustion chamber for petroleum coke particles in PCOS and less unburned particles emitted from the combustion chamber at low engine speed (1 200 r/min). Moreover, it can also be noticed from Fig. 10 that the diesel fuel consumption for PCOS is lower than that for diesel oil at 1 200 r/min. Thereby, the extinction coefficient for PCOS is similar to that for diesel oil before the maximum output power point for PCOS at 1 200 r/min (Fig. 13). When burning diesel oil at 1 200 r/min, richer mixture in the combustion chamber with the increase of the engine loads and incomplete combustion of abundant diesel fuel lead to the dramatic increase of extinction coefficient for diesel oil. However, owing to better combustion of petroleum coke particles in PCOS at low engine speed (1 200 r/min), the extinction coefficient for PCOS increases slightly and is lower than that of diesel oil under the same conditions.

The extinction coefficient for PCOS is always higher compared to diesel at 1 600 r/min. This is due to relatively short time to stay in the combustion chamber for petroleum coke particles in PCOS with the increase of engine speed and incomplete combustion of abundant petroleum coke particles emitted from the combustion chamber.

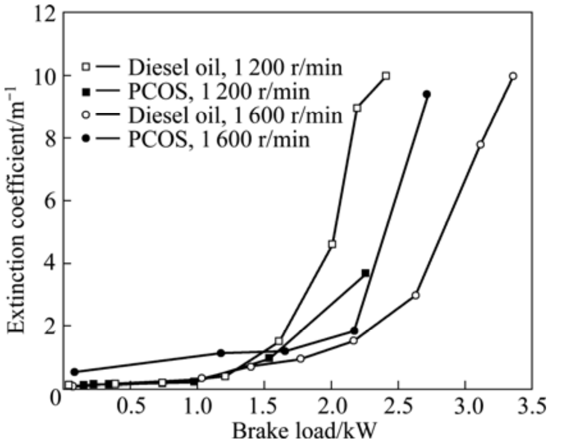

Fig. 13 Comparison of extinction coefficient for diesel oil and PCOS

The micro-morphology of the particles emitted when burning PCOS and diesel oil was investigated using scanning electron microscopy (SEM). The instrument for SEM is CamScan3400 from England. The micro-morphology of particles emitted when burning PCOS is shown in Fig. 14(a). It can be seen from Fig. 14(a) that the particles emitted when burning PCOS array sparsely, and the particles are covered by a small quantity of volatile organic compounds. Owing to incomplete combustion, the petroleum coke particles in PCOS are emitted from the combustion chamber and are dispersed with the fluctuation of the exhaust gas,

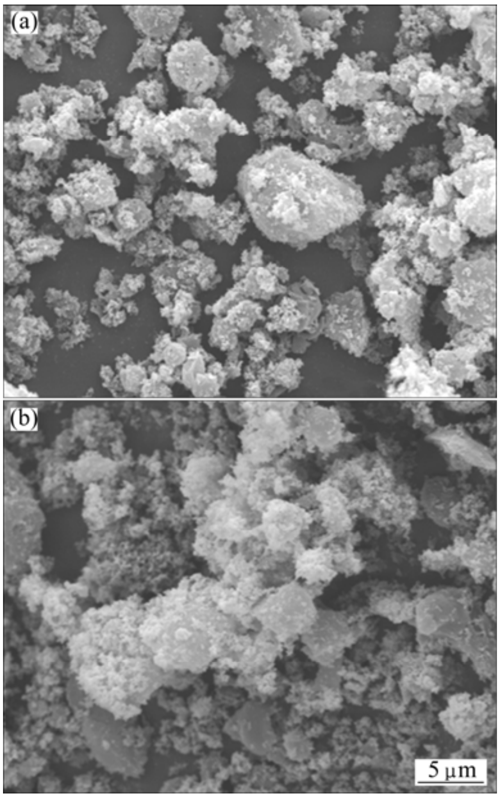

Fig. 14 Micro-morphologies of particles emitted when burning PCOS and diesel: (a) PCOS; (b) Diesel oil

simultaneously absorbing a small amount of HC of incomplete combustion. The micro-morphology of particles emitted when burning diesel oil is shown in Fig. 14(b). It can be seen from Fig. 14(b) that the particles emitted when burning diesel oil array closely, cohering together, and the particles are covered by a great deal of volatile organic compounds. This is because the soot particles produced due to incomplete combustion of diesel oil in the initial stage of diesel oil combustion collide with each other and become bigger particles, simultaneously absorbing a great deal of HC of incomplete combustion.

4 Conclusions

1) The PCOS engine fueled with PCOS can run steadily, and the needle valve assembly and the plunger matching parts in the PCOSFS are not clogged with the particles of PCOS.

2) The output power decreases and the exhaust gas temperature increases when burning PCOS compared to diesel oil. This is because of lower low heat value of PCOS, longer ignition delay and combustion duration for petroleum coke particles in PCOS compared to diesel oil.

3) The brake specific energy consumption of PCOS is lower than that of diesel oil. This is because of poorer atomization, lower efficiency of combustion for PCOS and longer ignition delay of petroleum coke particles in PCOS.

4) HC emissions for PCOS are lower compared to those for diesel oil at 1 200 r/min, and are close to those for diesel oil at 1 600 r/min. CO emissions of PCOS are close to that of diesel oil, and NO_x emissions are lower compared to diesel oil at 1 200 and 1 600 r/min. Smoke intensity of PCOS is higher than that of diesel oil with the increase of engine speed.

5) The particles emitted from the combustion chamber when burning PCOS mainly consist of incomplete combustion petroleum coke particles and little incomplete oxidation HC compounds, and array sparsely. The particles emitted from the combustion chamber when burning diesel oil absorb many incomplete oxidation HC compounds, and array closely.

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